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Evaluation of the Performance and Air Pollutant Emissions of Vehicles Operating on Various Natural Gas Blends

NGV Technology Forum

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Project Motivation

- Liquefied natural gas (LNG) and NG demand will increase over the next decades.
- California's current needs met largely by domestic and Canadian imports; future NG will be imported from Asia or other parts of the Pacific Rim.
- NG from foreign sources is expected to have more variation in composition and properties.
- Broader ranges of NG composition and properties could impact performance and/or emissions of vehicles.

Current Project

- Joint project with CEC with co-funding from SCAQMD
- Phase 1: Background literature survey and development of test plan with Technical Advisory Team
  - Review of literature and advisor recommendations indicate more testing of LDVs might be appropriate.
- Phase 2 Goal: Measure engine and vehicle performance, including emissions.
  - For a range of different LNG compositions
  - For a number of engine/vehicle technologies

Program Tasks

- Task 1 – Literature Review
- Task 2 – Develop Test Plan
- Task 3 – Test Engines
- Task 4 – Test vehicles/engines
- Task 5 – Final Report

Preparatory Tasks

- Task 1 – Literature Review
  - Convene Technical advisory committee
  - Review existing test data
  - Review information on gas composition (e.g., GTI report)
  - Provide suggestions for test engines/vehicles
- Task 2 – Develop Test Plan
  - Types of engines
  - Test cycles
  - Test fuels
  - Test procedures

Literature Results – Natural Gas Composition & Supply

- NG demand will increase 6.7% year (Jensen Associates)

- Supply composition
  - GTI studies in 1992 and 2006
  - CEC in 2005
  - PG&E Rule 21 and SoCalGas Rule 30
  - Natural Gas Council 2005
  - CARB new specifications for motor vehicles

Literature Results – Natural Gas Composition & supply

	Site	Methane (vol. %)	Heating Value (Btu/scf)	Wobbe Number (Btu/scf)
Northern California Region	1	93.92	1033	1340
	2	94.33	995	1301
	3	95.53	1017	1326
	4	96.64	1011	1336
	5	94.94	1026	1340
Southern California / San Diego Region	6	93.10	1039	1341
	7	93.73	1028	1335
Southern California / L.A. Region	8	93.60	1030	1335
	9	92.25	1040	1335
	10	91.19	1048	1337
	11	93.48	1029	1333
	12	92.34	1042	1340
Summary				
Average		93.09	1035	1337
Minimum		90.31	986	1290
Maximum		96.88	1060	1358

Table 2-1. Natural Gas Methane Content, Heating Value, and Wobbe Number in California Regions, 1992 (Liss et al.)

	Minimum	National Average	California Average	Maximum
Methane	74.5	93.9	93.1	98.1
Ethane	0.5	3.2	3.4	13.3
Propane	0.0	0.7	0.7	2.6
C_4 and higher	0.0	0.4	0.3	2.1
$N_2 + CO_2$	0.0	2.6	2.5	10.0

Table 2‑2. Natural Composition Information Compiled by the California Energy Commission (CEC/CPUC, 2005)

Literature Results – Natural Gas Composition & supply

Project Name	Location	Major Owners	Status	Typical LNG Composition	LNG Values
Sakhalin Energy	Russia, off east coast	Shell, Mitsui, Mitsubishi	Under construction, startup 2008	92.2% C1, 4.9% C2, 0.8% C3, 1.9% C4.	HHV=1105 Btu/scf SpG=0.613 Wobbe=1411
Darwin	Australia	ConocoPhillips	Under construction, 2008	Fields have high liquids content. LNG could be "hot".	*Unknown at present*
Malaysia TIGA	Malaysia	Petronas, Shell, Mitsubishi	Operational	91.2% C1, 5.2% C2, 3.3% C3, 1.4% C4+.	HHV=1137 Btu/scf SpG=0.633 Wobbe=1428 (EIA: 1122 HHV)
Northwest Shelf Train 5	Australia	Woodside, Shell, BP, BHP, Chevron, Mitsubishi/Mitsui	Under construction, 2006	89.3% C1, 7.1% C2, 2.5% C3, 1.0% C4+.	HHV=1128 Btu/scf SpG=0.628 Wobbe=1424 (EIA: 1132 HHV)
Tangguh Project	Indonesia	BP, CNOOC, MI Berau B.V. Nippon Oil Corp. KG Berau/Wiriagar LNG Japan Corp.	In EPC phase Startup 2008-2009	96.3% C1, 2.6% C2, 0.5% C3, 0.2% C4+, ,0.4% N2.	HHV=1039 Btu/scf SpG=0.590 Wobbe=1369 (EIA reports 1118 HHV)
Peru LNG	Peru	Hunt Oil, Repsol, SK	Planned; 2009	*Unknown at present*	*Unknown at present*
Pilbara	Australia	BHP Billiton, ExxonMobil	Pre-feasibility study	*95% C1, 5% N2*	*HHV=964 Btu/scf SpG=0.576 Wobbe=1270*

Table 2-3. Likely LNG Exporters to California

Literature Results – Natural Gas Composition & supply

Figure 2-2. California's Gas Supply and Representative Wobbe Numbers

Literature Results – LDV Composition

- GTI conducted study in 2006
  - Utilized a number of sources including the DMV, Bevilacqua-Knight, CARB, sales reports, and DOE information.
- Estimated number of LDVs in California is between 13,000 and 18,000
- 52-56% passenger cars (Civic, Crown Vic, Camry, etc.)
- 26-30% LD trucks (F-150)
- 16-18% vans/wagons (Chrysler minivan, full size vans)
- Conclusion: Based on current users, new CARB fuel rules will not create any serious issues with engine knock or driveability

Literature Results – HDV Composition

- SoCalGas and SDG&E conducted survey of heavy-duty CNG vehicles in greater Southern California in 2006
- 4,224 CNG vehicle identified
- 3,015 “legacy” not designed to operate on sub-80 methane number
- 75% transit buses, with the categories including school buses, waste haulers, street sweepers, and others
- LA county had the largest number of CNG vehicles/engines, with the majority of these being DDC TL platforms

Literature Results – HDV Composition

Engine Make and Model	Legacy Fleet[1] Engine?	Counties[2] (showing number of engines in 2005)													Total	
		Los Angeles	Orange	San Diego	Riverside	San Bernardino	Ventura	Santa Barbara	Kern	Kings	Tulare	San Luis Obispo	Imperial	Fresno	number	% of total
Detroit Diesel - "TK" (6047-TKG8)	Yes	1,427	0	128	94	0	22	0	0	0	0	0	0	0	1,671	39.6%
Cummins - L10 Phase 3	Yes	605	0	0	18	0	0	0	0	5	0	0	0	0	628	14.9%
John Deere - 6081H	No	228	54	115	77	52	17	12	8	2	27	18	3	12	625	14.8%
Cummins - C8.3G Plus	No	104	34	208	50	37	0	0	2	0	0	1	0	0	436	10.3%
Detroit Diesel - "MK" (6047-MKG8)	Yes	290	0	0	0	0	10	0	0	0	0	0	0	0	300	7.1%
Cummins - C8.3G	Yes	25	19	70	64	11	9	0	0	0	0	0	0	0	198	4.7%
Cummins - B5.9G Plus	No	66	4	7	0	14	2	0	0	0	0	0	0	0	93	2.2%
Cummins - B5.9G	Yes	26	0	27	40	2	2	2	2	1	0	0	0	0	102	2.4%
Cummins - L10 Phase 1	Yes	0	0	1	31	0	0	0	0	0	0	2	0	0	34	0.8%
Detroit Diesel - "GK" (6047-GKG8)	Yes	4	0	0	3	0	16	0	0	0	0	0	0	0	23	0.5%
Cummins - L Gas Plus	No	30	2	0	0	0	0	0	0	0	0	0	0	0	32	0.8%
John Deere - 6068H	No	4	0	16	0	0	0	0	0	0	2	1	0	0	23	0.5%
Cummins - L10 Phase 2	Yes	0	0	0	22	0	4	0	0	0	0	0	0	0	26	0.6%
Caterpillar - Dual Fuel	Yes	4	16	0	0	0	0	0	0	0	0	0	0	0	20	0.5%
Tecogen	Yes	0	0	0	0	0	0	2	0	0	0	9	0	0	11	0.3%
Mack - E7G	Yes	1	0	0	1	0	0	0	0	0	0	0	0	0	2	0.0%
Total	number	2,814	129	572	400	116	82	16	12	8	29	31	3	12	4,224	100.0%
	%	67%	3%	14%	9%	3%	2%	0%	0%	0%	1%	1%	0%	0%	100%	-
Total (Legacy Fleet only)	number	2,382	35	226	273	13	63	4	2	6	0	11	0	0	3,015	-
	%	79%	1%	7%	9%	0%	2%	0%	0%	0%	0%	0%	0%	0%	100%	-

Table 3–1. Heavy Duty NG Engines Operating in the Southern California Region of SoCalGas and SDG&E in 2005 (Harte, 2006)

Literature Results – NG engines

- Cummins/Westport
  - Earlier models – L10, C-Gas Plus
  - B Gas Plus, ISL G
- Detroit Diesel Corporation
  - Series 50G engine — "GK" 94-98 — "TK" 98-02 – "MK" 02- end production
- John Deere
  - 8.1 L 6081 engine
- Mack
  - 12 L Eco-Tech E7G plus some other research efforts
- Others
  - Caterpillar conducted some published development studies
  - Next Generation Vehicle Program
    - Teleflex/General Motors, Clean Air Partners
  - Hercules 5.6L NG engine in mid-1990s

Literature Results – Emissions/Performance Studies SoCalGas

- NG compressor in Ventura County (2003)
  - Emissions showed considerable variability
- Second rich-burn NG gas compressor
  - Linear correlations between NOx and Wobbe Number, CO and HHV, and VOCs and VOC composition
- Paper Studies
  - 5 different Cummins engines
  - 3 different DDC engines (GK, TK, MK)
  - Open loop systems could experience knock on rich mixtures
- Studies at/with Southwest Research (SwRI)
  - Engine testing on an MK and TK
    - Emissions did change with fuel composition with NO_x increasing with increasing Wobbe #
  - Field study with Los Angeles Metropolitan Transit Authority
- Ongoing work at SwRI
  - A number of engines and fuel blends

Literature Results – Emissions/Performance Studies
National Energy Technology Laboratory

- Conducted literature review
  - Fuel composition impact in vehicles/engines
  - Fundamental studies of combustion
- Some in-house tests
- Concluded most modern engines have A/F control that will reduce/eliminate impacts of Wobbe Index and Methane Number (MN)
  - Closed loop systems will not have significant emissions impact from differing LNG mixtures
  - Open loop systems may see small changes in CO, NO_x, and NMHC from differing LNG mixtures
  - Most engines certified to operate on a MN >80
- Some points appear to contradict other available literature

Literature Results – Emissions/Performance Studies Other Studies

- Field Studies focusing on CNG
  - Sunline
  - Washington Metropolitan Area Transit Authority
  - Norcal
  - US Postal Service
- Emissions Testing by West Virginia University

Light-Duty Vehicle Testing

- Testing in CE-CERT’s Vehicle Emissions Research Laboratory
- 2 Vehicles
  - Late model, SULEV certified Honda GX
  - Ford Crown Victoria with BAF certified retrofit kit, SULEV certified
  - High population within DMV database
  - Vehicles to be obtained through SCAQMD
- 2 to 4 fuel blends
- Test cycles with be FTP and Unified Cycle with 3 replicates on each fuel
- 50 mph preconditioning drive on each new fuel tested

Engine Testing

- Primary testing in CE-CERT’s Engine Dynamometer Test Facility
- 1-3 Engines
  - Engines to be certified to 2010 standards (Westport LNG, ESI, ISL G)
  - Reduction in number of engines due to PAC emphasis on testing light-duty vehicles and on chassis dynamometer testing.
  - Exploring the possibility of testing the Westport LNG at their test facility.
- 4 fuel blends
- Test cycles could include: FTP, AVL 8 mode

Vehicle Chassis Dynamometer Testing

- Testing at CE-CERT chassis dynamometer facility/or another local facility
- 2+ Vehicles (chassis dynamometer testing was emphasized by PAC)
- 4 fuel blends
- Test cycles to be determined

Gas blends for Testing

- A gas representative of pipeline gas.
- Gas that meets CARB natural gas specifications. Properties consistent with an average gas were selected.
- A blend with a high Wobbe number that is representative of a gas that would be on the “hotter” end of the gas that might wind up in the marketplace.
- A blend where the high Wobbe number gas is blended with N_2 to bring the Wobbe number down to 1385.

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Proposed Gas blends for Testing

Gas #	Description	methane	ethane	propane	I-butane	N2	MN	Wobbe #	HHV
1	Baseline, Line gas	96.08	1.78	0.37	0.16	1.62	100	1344	1020
2	CARB spec gas	90.3	4	2		3.7	89	1330	1038
3	1150 BTU, Hi Wobbe	87.03	9.23	2.76	0.99	0	75	1436	1150
4	modified gas 3	84.5	8.9	2.7	1.0	2.85	74	1385	1118